Integrated Inspection for Precision Part Production

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Motivation

• Precision machining
  – Smaller custom jobs
  – Tight tolerance
  – Procedure
    • Cut part, remove part, then inspect
    • Scrap or setup workpiece again

  – Correct before removal
Objective

• **Develop methodology** to improve machine tool (MT) performance
  – cut circular arc (hemishell)
  – on 2-axis lathe

  – **Straightforward** to implement
    • G-code

  – Utilizes commercially available hardware
    • Ball bar, on-machine probe (OMP), tool set station
Cut Circular Trajectory

- Workpiece with circular trajectory
- “Hemishell”
  - “Easy to machine”
  - Incorporates movement of both axes
  - No backlash
2-Axis Vertical Turning Lathe

**Repeatability:**
- X: 2.5 μm (0.0001 in)
- Z: 5.1 μm (0.0002 in)

**Resolution:**
- 0.0001 in
- (0.00254 mm)

Okuma & Howa V40R, schematic and photo.
Machining Procedure

- Error Model
- Modify part program
- Inspect On-machine
- Tool set
- Chuck the workpiece
- Run part program
- Remove part
- Inspect

pre-process

process-intermittent
Equipment

• Ball bar (Pre-process)
  – Measures motion only

• OMP (Process-intermittent)
  – Includes motion and cutting effects

• CMM (Post-process)
  – Final inspection
Ball Bar

- Renishaw QC10

- Characterizes circular trajectory

- Particularly relevant
Touch Probe Inspection

- **OMP**
  - Process intermittent inspection
  - Traditionally used for datum location

- **CMM**
  - Post-process inspection
Compensation Strategy

• Based on
  – Ball bar
  – OMP

• Modify part program (G-code)
Generate New Trajectory

- "Given nominal and measured"
Ball Bar Compensation

<table>
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<tr>
<th>mm</th>
<th></th>
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<tbody>
<tr>
<td>original</td>
<td>-0.001</td>
<td>0.000</td>
</tr>
<tr>
<td>standard deviation of error</td>
<td>0.007</td>
<td>0.001</td>
</tr>
</tbody>
</table>

Original Ball Bar Trajectory
Compensated Ball Bar Trajectory
The diagram shows a workpiece with labeled features:
- **Center line**: Horizontal datum
- **Pole, 0°**: Vertical datum
- **Equator, 90°**: Horizontal datum
Ball Bar-Based Compensation

![Graph showing deviation from nominal (mm) vs. angle (degree)]

<table>
<thead>
<tr>
<th></th>
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<tbody>
<tr>
<td>average error</td>
<td>-0.002</td>
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<tr>
<td>standard deviation of error</td>
<td>0.006</td>
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OMP Compensation

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<tr>
<td>OMP of run 1 (uncomp.)</td>
<td>-0.004</td>
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<tr>
<td>OMP of run 2 (comp.)</td>
<td>0.001</td>
</tr>
<tr>
<td>CMM of run 2</td>
<td>0.002</td>
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</tbody>
</table>

**Average error**

- OMP of run 1 (uncomp.): -0.004 mm
- OMP of run 2 (comp.): 0.001 mm
- CMM of run 2: 0.002 mm

**Standard deviation of error**

- OMP of run 1 (uncomp.): 0.004 mm
- OMP of run 2 (comp.): 0.002 mm
- CMM of run 2: 0.003 mm
OMP Compensation

- Large tool set error

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<th>CMM of run 2</th>
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<td>average error</td>
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Conclusions

• Ball Bar-based cutting compensation
  – Current method unsuccessful
  – Different method? Other factors?

• OMP-based cutting compensation
  – Limited by inspection accuracy (machine repeatability)
  – Accounts for errors
Contributions

- Developed a methodology for integrating inspection and machining on a vertical turning lathe

- Developed a strategy for predicting and compensating trajectory errors

- Characterized utility of on-machine probe, ball bar, tool set station, and tool set station for precision machining

- Improved the accuracy of circular tool paths for the Okuma & Howa V40R
Questions